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An evaluation of repair mortars installed by worm-pump spraying

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ABSTRACT: This paper examines the fresh and hardened performance of wet-process sprayed mortars and the influence of rheology on the pumping and spraying of these mortars. Seven commercially available pre-blended repair mortars designed for hand application, together with a laboratory-designed fine mortar, were investigated using the Tattersall two-point rotational viscometer, the pressure bleed test, the slump test, and a vane shear strength test. The mortars were pumped and sprayed with a small diameter worm pump and the build thickness determined. Hardened properties measured include compressive strength, tensile bond strength, hardened density and drying shrinkage. Tests were conducted on cast and in-situ specimens and, where possible, on specimens produced by spraying directly into a cube or beam mould. Initial findings for predicting the pumpability and sprayability of the mortars are presented and this is linked together with the hardened performance. These results show that the majority of proprietary pre-blended repair mortars designed for hand application are suitable for wet-process application with a worm pump.

1 INTRODUCTION

Sprayed mortar can be defined as a mortar conveyed through a hose and pneumatically projected at high velocity from a nozzle into place. The rheological properties of the mix in the wet process are obviously critical. These properties have been examined by the authors in previous papers (Austin et al. 1999a and 1999b). The mortar's hardened properties are of equal importance, so that a durable and long lasting repair can be obtained, and these properties have also been investigated by the authors (Austin et al. 2000a). The findings of this work have also contributed to a Technical Report published by the authors in conjunction with the Concrete Society (Austin et al. 2000b).

This paper describes some of the findings of a three year UK Government and industry funded research programme into wet-process sprayed concrete for repair, and more specifically the fresh and hardened properties of a range of mortar mixes, which are defined as mixtures of cement, aggregate with a maximum particle size of 3 mm, water and any admixtures. The mortars tested include seven commercially available pre-blended concrete repair mortars and a generic mix design consisting of crushed Portland stone, Portland cement (PC), silica fume and a styrene butadiene rubber liquid additive (SBR).

2 WET PROCESS SPRAYED MORTARS

Wet process sprayed application offers a number of advantages over cast and hand-applied repairs, including the reduction or elimination of formwork, the construction of free form profiles and faster and more efficient construction (Austin 1997). It can also provide enhanced hardened properties if properly placed.

Previous work published by the authors have discussed both the materials, installation and physical properties of sprayed concrete (Austin 1995a) and the associated application methods and quality considerations (Austin 1995b).

Browne & Bamforth (1977) showed that it is possible to change from a saturated to an unsaturated state by excessive loss of mix water due to pressure, thus increasing frictional stress, and even blockage. A concrete that de-waters quickly under pressure will be prone to blocking in a pipeline. Beaupré (1994) investigated the rheological properties of sprayed concrete and the relationship between pumpability and sprayability, including the development of predictive models based on yield and flow resistance determined from tests conducted with a rotational viscometer.

Tattersall (1976) developed a rheometer, termed the two-point test apparatus and found that when the torque (T) was plotted against the speed (N) for de-

creasing results only, the relationship was almost linear:

$$T = g + hN \quad (1)$$

where g is the intercept on the torque axis and h the slope of the line. Beaupré (1994) referred to g as the flow resistance, and h as the torque viscosity. This equation is of the same form as the Bingham model ($\tau = \tau_0 + \mu \cdot \dot{\gamma}$) and thus it can be said that g is a measure of yield value, and h of plastic viscosity.

Hills (1982) conducted tests on both wet- and dry-process sprayed concrete, and compared results with those from cast concrete. He concluded that the performance of the sprayed concretes did not appear significantly different from those of properly compacted cast mixes of similar composition and he argued that it was the modified mix design needed for sprayed concretes that altered the hardened properties, not the method of placement. However, Banthia et al. (1994) have argued that cast and sprayed concrete are of a different nature, with the spraying process affecting the internal arrangement of constituents and hence the strength and durability.

Work conducted by Gordon (1991) on wet-sprayed pre-blended repair mortars concluded that the wet process achieves greater compaction than hand application and that the materials tested achieved compressive strengths approximately 30% higher when wet sprayed than when hand applied. Increases in fresh wet density, bond strength and build were also recorded.

3 EXPERIMENTAL PROGRAMME

A number of pre-blended proprietary mortars designed for hand application were investigated (Table 1). In order to obtain the aggregate/cementitious ratio the mortars were sieved and the particles collected on each sieve were examined under a x40 magnification microscope. The approximate proportion of aggregate, lightweight filler (approx. 75-300 μ m in diameter) or cementitious material on each sieve (to the nearest 10 %) was determined and the weight of each calculated accordingly.

The laboratory-designed mortar D1w was a 3:1 crushed Portland stone : Portland cement mix with 5% silica fume (by weight of cement) and an SBR in a 1:3 solution with water. All the mortars were mixed to a consistency which would be typical for low-volume sprayed application.

The mortars were mixed using a 0.043 m³ capacity forced-action paddle mixer according to the manufacturers instructions, with 3.3 to 4.0 litres of water per 25 kg bag of dry material for approximately 4 minutes. The mortars were pumped with a Putzmeister TS3/EVR variable-speed worm (i.e. screw-type) pump with a 25 mm diameter rubber hose, an air pressure of 300 kPa and an output of approximately 6 L/min. The mortars were sprayed into 500 \times 500 \times 100 mm deep panels whilst trying to minimize both voids and rebound. Mix P2 was also sprayed with a large diameter worm pump (termed P2W) and mix P1 with a piston pump (termed P1p).

3.1 Fresh property testing

The workability was measured by the slump test (BS1881: Part102: 1983) and by a modified form of the shear vane test for soils (BS 1377: Part 9: 1990). The shear vane consisted of a torque measuring device at the head of the instrument together with a set of vanes to provide sufficient shear resistance to register on the torque scale. The shear strength for the mortar (in kPa) was then calculated from the maximum torque. The pressure bleed apparatus (Browne & Bamforth 1977) consisted of a 125 mm diameter steel cylinder lined with a 75 μ m mesh on the inside of the base and a bleed hole with a stop tap located beneath the mesh. The apparatus was filled with approximately 1700 cm³ of mortar and subjected to a load of 12.2 kN, equivalent to 10 bar (1000 kPa), which was the highest pumping pressure recorded with the TS3EVR worm pump. The valve was opened after 10 seconds and the liquid emitted collected on a digital balance and the change in weight was data-logged for 30 minutes. Sprayability was assessed both qualitatively (did the material pass through the nozzle) and quantitatively (in terms of the amount of material that could be built up on a vertical grit-blasted concrete substrate).

Table 1. Composition of mortars (P:Pre-blended, D:Designed mix, w/W: small/large diameter worm pump, p: piston pump)

Mix	Water/ cementitious Ratio	Aggregate/ cementitious Ratio	Polymer Modified	Polypropylene Fibres	Shrinkage Compensators	Light- weight Filler	Description
P1w	0.59	2.3	N	N	Some	N	Basic repair mortar
P2w	0.41	1.45	Y	Y	Y	Y	High build repair mortar
P3w	-	1.58	Y	Y	Y	Y	2-part re-profiling mortar
P4w	0.47	2.31	Y	Y	N	Y	Basic repair mortar
P5w	0.39	1.33	Y	Y	N	Y	Repair mortar
P6w	0.45	1.62	Y	Y	Y	N	Repair mortar
P7w	0.90	3.42	Y	Y	Y	Y	Lightweight mortar
P1p	-	2.3	N	N	Some	N	Piston pumped
P2W	-	1.45	Y	Y	Y	Y	Large diameter worm pump
D1p	-	3:1	Y	N	N	N	Designed (piston pumped)

The mortar was sprayed horizontally onto a 300×300 mm target area in order to obtain as large an amount of material as possible on the substrate whilst keeping within the ‘target’. The mortar would then fail under its own weight either cohesively, adhesively or a combination of both. The sprayability was also measured in terms of the reinforcement encasement.

This test consisted of a 500×500×100 mm deep panel fitted with steel reinforcement of 8 and 12 mm diameters at 100 mm centres with some of the bars placed in pairs to produce an effective maximum thickness of 24 mm. The panel was sprayed to obtain as complete encasement as possible. At 28 days the intersections of the bars were cored and a 5 mm disc was cut from the bottom (i.e. moulded face) of the 55 mm diameter core and discarded. A 20 mm thick disc was sawn from the same end and a sorptivity test conducted on both the disc and the remainder of the core. The sorptivity was then related to the density of the reinforcement at the bar intersection.

3.2 Hardened property testing

All material within 50 mm of the panel edge was discarded to avoid the effects of rebound entrapment around the edges of the moulds. All samples were sawn approximately 24 hours after spraying and cured under water at 20±2°C. The specimens sprayed and cast into steel moulds were struck and cured in the same manner.

Cores were capped with a sulphur compound, whilst sawn cubes were capped with a 2-3 mm layer of high-strength plaster between steel plates due to the imperfect orientation and texture of the sawn sides. Compressive cube tests were carried out at 28 days in accordance with BS1881: Part116: 1983 and the compressive core tests were conducted at 28 days in accordance with BS1881: Part120: 1983.

The tensile bond strength was measured by a core pull-off test (using the Limpet apparatus (McLeish 1993)) at 7 and 28 days. Five 55 mm diameter partial cores were cut through the repair material and into the concrete substrate (which had been grit-blasted) to a depth of approximately 10 mm and a 50 mm diameter steel dolly was then glued to the top of the core and an axial tensile load applied at a rate of 2 kN/min to failure.

The saturated hardened densities of the cubes were calculated by weighing in air and determining their volume from measured dimensions.

Prisms to monitor drying shrinkage vary according to different standards, although even the largest are too small to spray directly into a mould. 75×75×229 mm specimens were therefore cast to BS1881: Part5: 1970 and also sawn from the sprayed panels. Pairs of demec pips were glued to three of the longitudinal faces on a 200 mm gauge

length and the specimens were stored in a climatic cabinet at 20°C and 50% RH.

4 TEST RESULTS

4.1 Fresh properties

The shear vane provides a basic measure of the shear strength (in kPa) of a mortar and this is plotted against slump (in mm) in Figure 1. As would be expected, this shows a decrease in shear strength for an increase in slump. The shear vane test can provide an instantaneous result exactly where the rheological properties of the mortar needs to be measured, e.g. in the hopper of the pump.

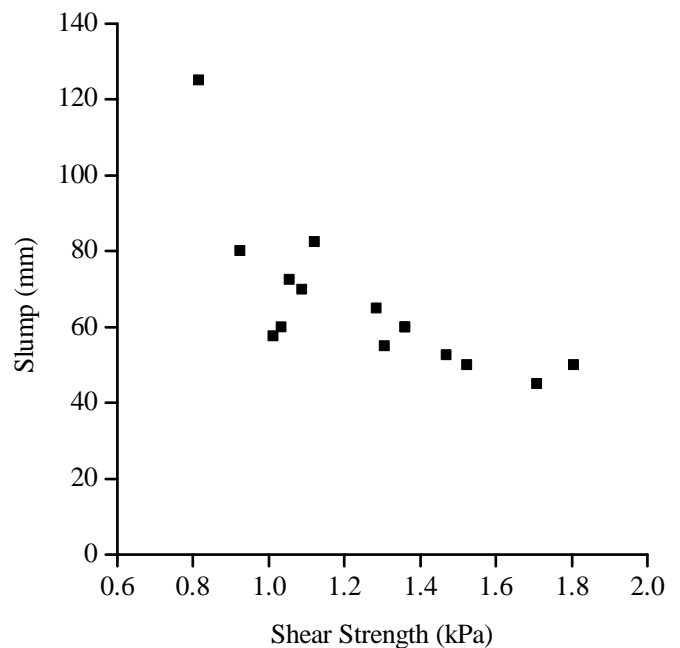


Figure 1. Shear vane strength compared with slump.

Figure 2 shows the flow resistance (g) and plastic viscosity (h) for the mortar P2 after it has been mixed, pumped and sprayed.

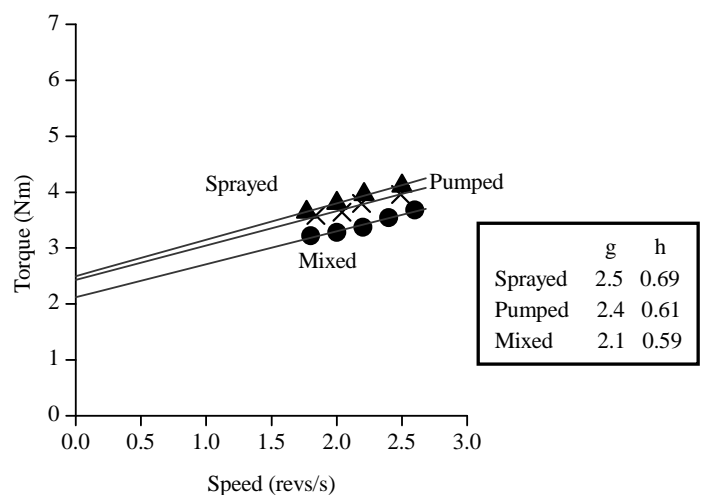


Figure 2. Two-point test: effect of mix P2 being mixed, pumped and sprayed.

The increase in the values of both g and h as the mortar is pumped and then sprayed would be ex-

pected as the excess air is forced out of the mortar. The two-point test results for all the mortars in this study are shown in Figure 3.

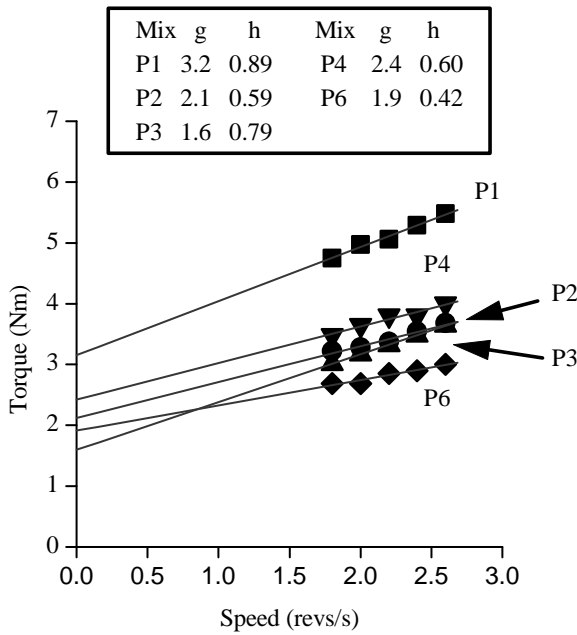


Figure 3. Two-point test: pre-blended mortars.

The pre-blended mortar with both the highest g and highest h values was mix P1 which had the most ‘basic’ mix design of all the pre-blended mortars tested, and contained no polymers, fibres or lightweight fillers. The mix with the next highest value of g , P4, also had a relatively basic mix design and together with P1 were the cheapest commercially of all the pre-blended mortars that were tested. The two highly polymer-modified mixes (P6 and P3) had the lowest values of g , although their corresponding values of h were very different. The mix P3 is a two-part (powder and liquid) re-profiling mortar which had been formulated to enable it to be applied in thin layers without it separating or being too ‘sticky’, which may explain why it had the smallest value of g .

Figure 4 shows that the total liquid emitted from the pre-blended repair mortars in the first 30 minutes ranged from 20 to 140 mL. This liquid was a combination of water, SBR, Portland cement, silica fume and very fine ($<75 \mu\text{m}$) sand particles. The relatively basic mortars (P1 and P4) that contain little or no polymers emitted the largest total amount of liquid at the fastest rate and the highly polymer-modified mixes (P6 and P7) emitted a smaller total amount of liquid at a slower rate. The two-part re-profiling mortar (P3) emitted a small amount of liquid (20 mL) very quickly in the first 2.5 minutes but then the rate of bleeding decreased rapidly. The resistance of a mix to bleeding is dependant upon the mix composition, especially the grading of the constituents and the mixes examined here with the lowest proportion of fine material emitted the most liquid and vice versa.

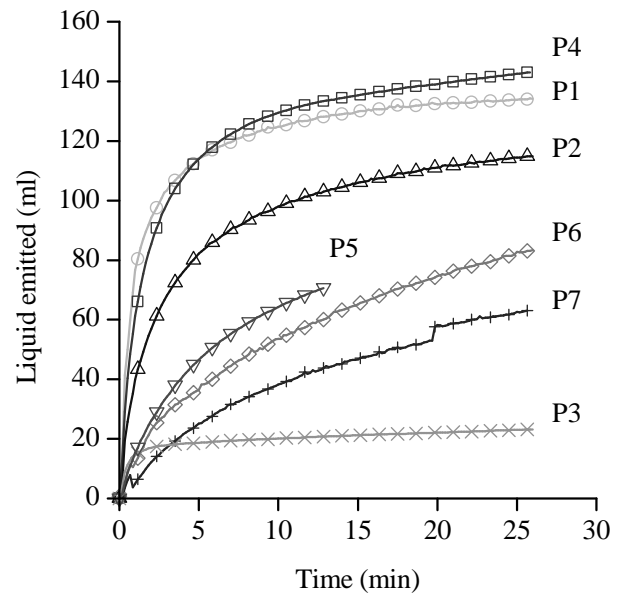


Figure 4. Pressure bleed test

The build compared with the slump before pumping is shown in Figure 5. This indicates an increase in build as the slump increases from zero until a slump of approximately 60 mm is reached, at which point the build begins to decrease. The relationship is not distinct due to the variability in the mix designs of the mortars. Beaupré (1994) found no correlation between slump before pumping and build, although he did conclude that a correlation could exist between concretes of the same mix design. As the slump decreases the mortars change from a cohesive failure (within the fresh material) to an adhesive failure (at the substrate), these failure modes being indicated on the Figure. This change in failure mode could possibly account for the build of the mortars increasing as the slump decreases until a slump of approximately 60 mm when the build appears to fall for a decrease in slump.

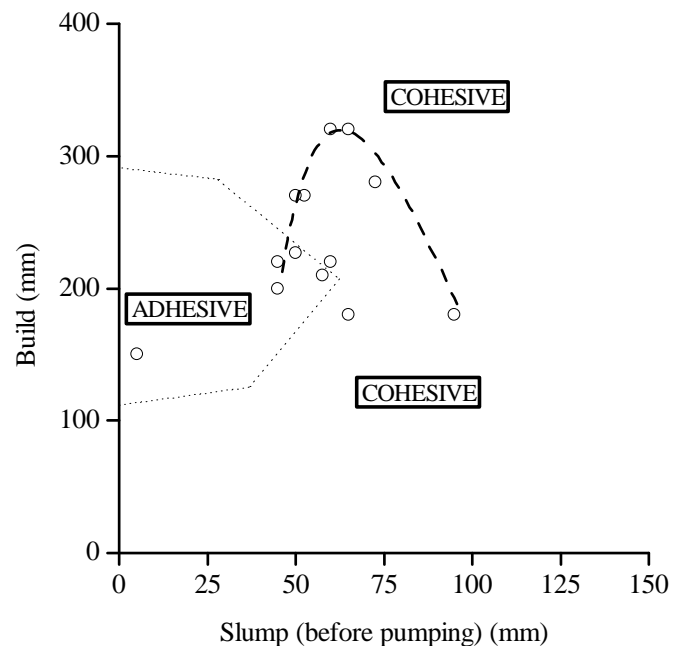


Figure 5. Build compared with slump (before pumping).

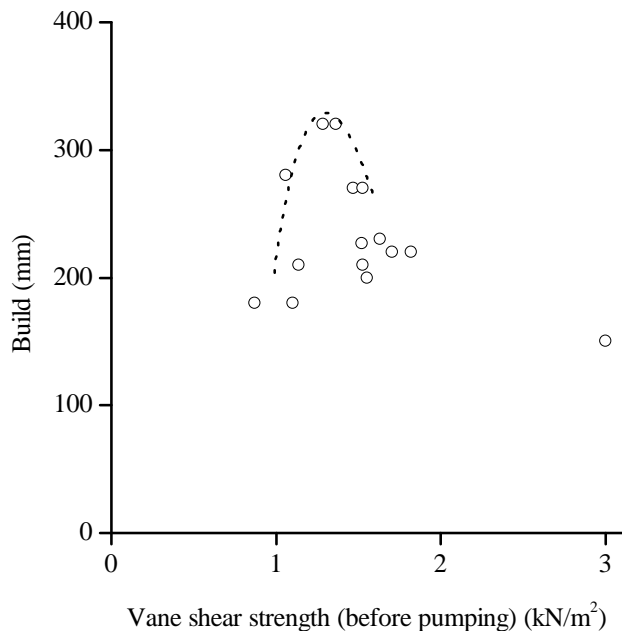


Figure 6. Build compared with vane shear strength (before pumping).

Figure 6 suggests that the build at first increases with increasing vane shear strength, and then begins to decrease at a vane shear strength of approximately 1.4 kN/m^2 , as would be expected due to the relationship between the slump and the vane shear strength (Fig. 1).

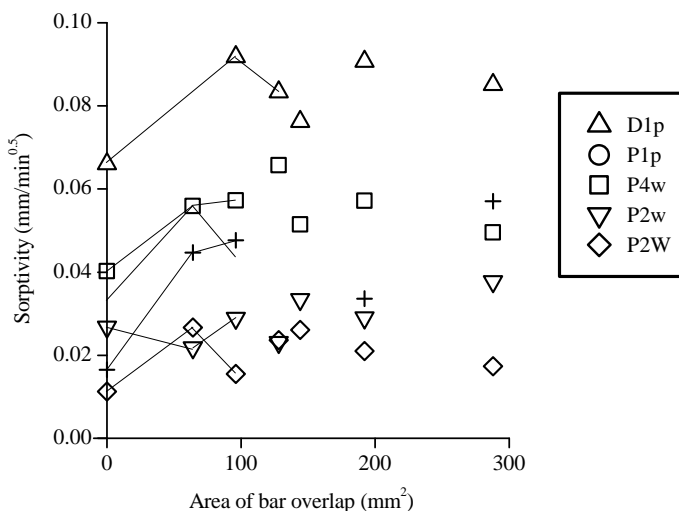


Figure 7. Reinforcement encasement: sorptivity compared with area of bar overlap.

The influence of the density of reinforcement on the sorptivity (of the top of the core, i.e. the material just behind the bars) is shown in Figure 7. Note that the sorptivity of all the mortars except P2W increases between bar overlaps of zero and 96 mm^2 , and then levels off and only increases slightly as the bar overlap area increases. Trend lines are shown on the first two points of each mortar for clarity. The bar overlap area was taken as the cross-sectional area on plan of the intersection of the bars (e.g. $8 \times 12 \text{ mm} = 96 \text{ mm}^2$). In general, the sorptivity of the pre-blended mortars does not increase greatly as the density of reinforcement increases. A reinforcement

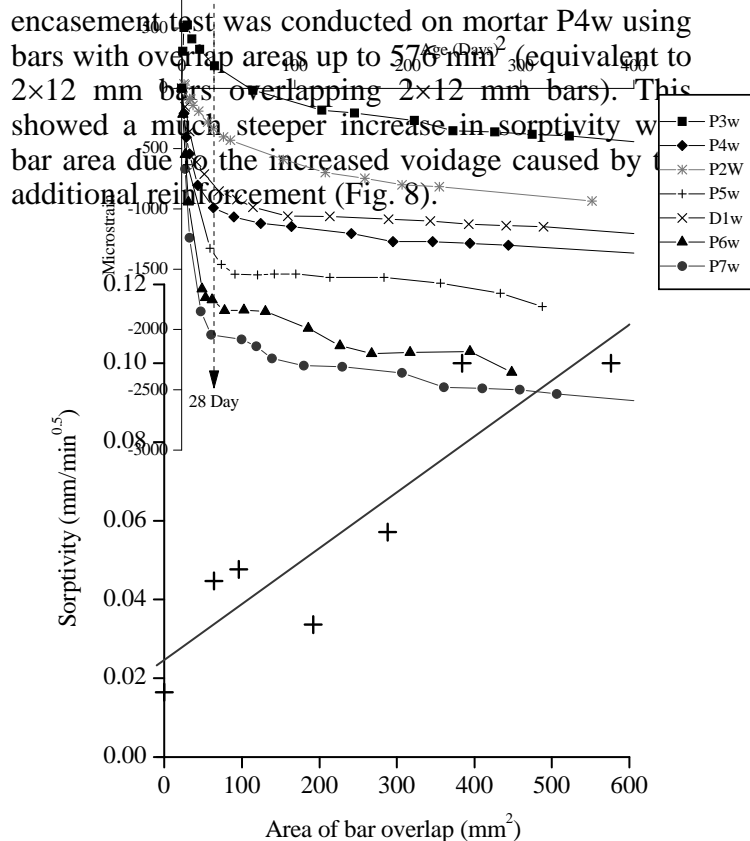


Figure 8. Mix P4w reinforcement encasement: Sorptivity compared with area of bar overlap.

4.2 Hardened properties

Figure 9 shows the equivalent cube strengths of the worm-pumped mortars obtained from in-situ cores, cubes cut from panels, and the cast and sprayed cubes. The mortars with the lowest strengths of 26-34 MPa were, as expected, obtained with the render/profiling and lightweight repair mortars (P3w and P7w). The simple laboratory designed mix D1w produced the highest strengths compared to the more sophisticated (and therefore expensive) pre-blended mortars.

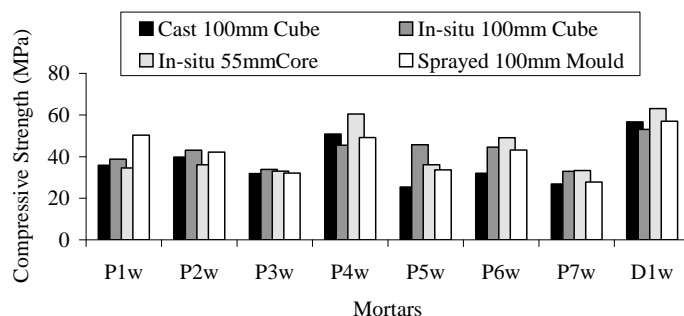


Figure 9. Compressive strengths of mortars.

The in-situ cube strengths are generally higher than the corresponding cast cubes, due mainly to the greater compaction obtained with the spraying process. This greater compaction can be seen in the greater densities of the in-situ cubes compared with the corresponding cast cubes (Figure 10). It is gener-

ally agreed that in-situ sprayed concretes produce higher strengths than for similarly cast mixes although the opposite has also been observed (Banthia et al., 1994). P5w, P6w and P7w have low cast cube strengths (and correspondingly low cast densities) as these specimens contained a large number of air voids, even after considerable vibration. There is a good correlation between the in-situ cube strengths and the cubes sprayed in moulds, despite the difficulty in obtaining a sample with no voids and low rebound (samples with excessive voidage being discarded).

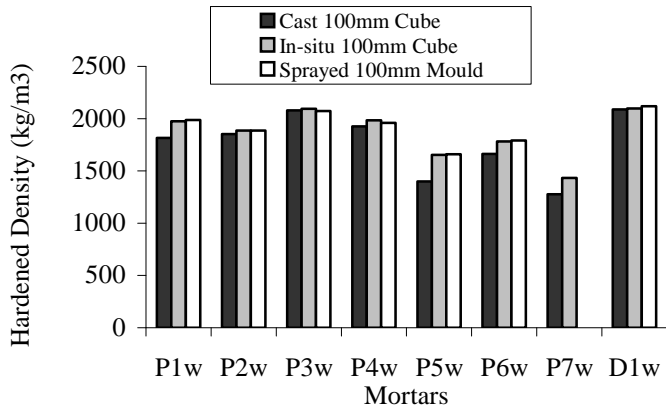


Figure 10. Hardened density of mortars.

The vertical and overhead bond strengths of the small worm pump mortars are shown in Figure 11. All the pre-blended mortars achieved at least 1.7 MPa at 28 days (with the exception of the lightweight mortar P7) which comfortably exceeds the Concrete Society minimum bond strength of 0.8 MPa. The mortars in this study (except P7) possess a relatively narrow range of vertical bond strengths (1.7-2.25 MPa), despite having a broad range of in-situ compressive strengths (32-57 MPa).

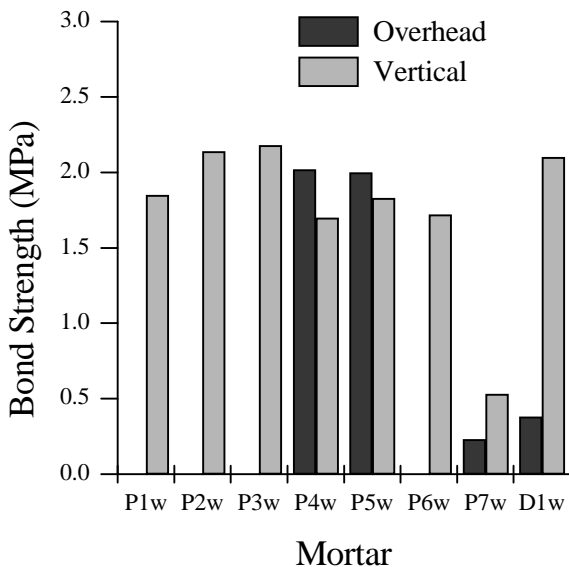


Figure 11. Bond Strength Overhead and Vertical at 28 days

Figure 12. Drying shrinkage of prisms taken from in situ material.

The drying shrinkage results for the 75×75×229 mm in-situ prisms are shown in Figure 12. A wide range of results were obtained, despite all the pre-blended mixes being described as low shrinkage. P2W and P3w expanded initially due to the presence of shrinkage compensators. However, the inclusion of these admixtures appeared to have little affect on the other mortars containing shrinkage compensators (P6w and P7w). The mortar which shrank the greatest at the fastest rate was the lightweight mortar P7, which would be expected due to the very high water/cementitious ratio.

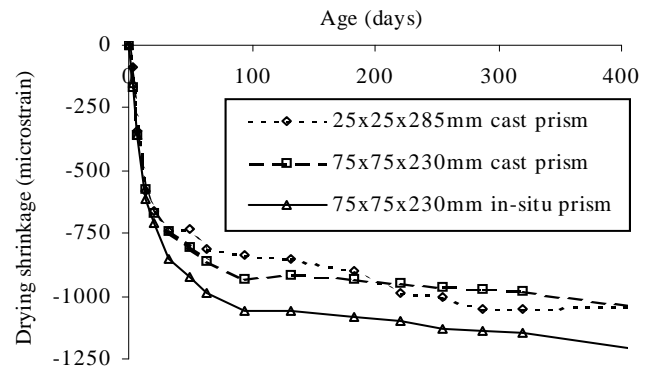


Figure 13. Drying shrinkage: mix D1.

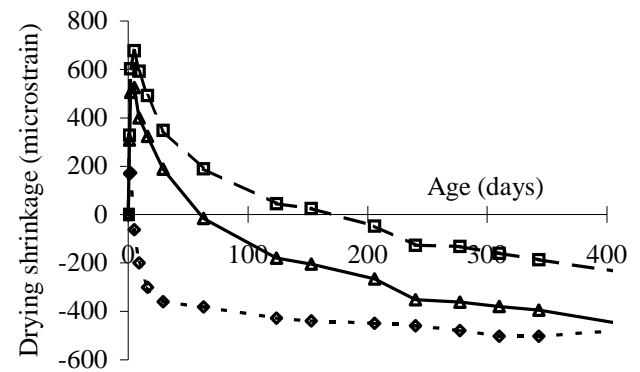


Figure 14. Drying shrinkage: mix P3w.

The rates of drying shrinkage for three types of prism (from an average of two samples) are shown for mix D1 in Figure 13 and for mix P3w in Figure 14. The larger (75×75×229 mm) in-situ prisms had the highest total drying shrinkage for the designed-mix D1w (approximately 1200 microstrain at 1 year), possibly due to the greater compaction and slightly lower aggregate content (due to differential rebound) compared with the cast samples. However, the shrinkage-compensated pre-blended mix P3w expanded before it began to shrink. This demonstrates that care should always be taken when quoting drying shrinkage values, especially when shrinkage-compensators are present, as the dimensional

change of the sample can be very different depending on the age and size of the sample.

5 CONCLUSIONS

This paper has presented and discussed a variety of data on the rheological and hardened performance of wet-process sprayed mortars and shows that proprietary pre-blended repair mortars designed for hand application are suitable for wet-process application with a small-diameter worm pump.

A shear vane test has been developed and a good correlation with the slump has been found. The two-point apparatus was successful with low-workability mortars and their flow resistance and torque viscosities were determined. The pressure bleed test demonstrated that the presence of an SBR significantly influences both the rate and total emission of liquid from the mix under pressure. The proportion of fine material and the water content of the mix were also crucial factors in the amount and rate of liquid emitted. A test was devised to quantify the degree of reinforcement encasement and in general the sorptivity (which was related to the amount of voidage behind the bars) did not increase greatly as the density of reinforcement increased.

The relatively simple laboratory-designed mortar possessed high compressive strengths compared with the proprietary pre-blended mortars. There was a good correlation between the in-situ and the sprayed mould compressive cube strengths, providing that no large voids or excessive rebound is present. Except for the lightweight mortar P7w, all the mortars possessed a relatively narrow range of bond strengths compared with their compressive strengths. The cast and the in-situ prisms exhibited very similar rates of drying shrinkage, suggesting that cast prisms could be used for quality control purposes to measure and monitor in-situ drying shrinkage.

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